

J/ψ production at $\sqrt{s} = 1.96$ and 7 TeV: Color-Singlet Model, NNLO^{*} and polarisation

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Abstract. We study J/ψ production in pp collisions at $\sqrt{s} = 1.96$ and 7 TeV using the Colour-Singlet Model (CSM), including next-to-leading order (NLO) corrections and dominant α_s^5 contributions (NNLO^{*}). We find that the CSM reproduces the existing data if the upper range of the NNLO^{*} is near the actual –but presently unknown – NNLO. The direct yield polarisation for the NLO and NNLO^{*} is increasingly longitudinal in the helicity frame when P_T gets larger. Contrary to what is sometimes claimed in the literature, the prompt J/ψ yield polarisation in the CSM is compatible with the experimental data from the CDF collaboration, when one combines the direct yield with a data-driven range for the polarisation of J/ψ from χ_c .

1. Introduction

The numerous quarkonium-production puzzles at hadron colliders were attributed not too long ago to non-perturbative effects associated with channels in which the heavy quark-pair is produced in a colour-octet state [1]. α_s^4 and α_s^5 corrections to the CSM [2] are now widely recognised as essential to understand the P_T spectrum of J/ψ and Υ produced in high-energy hadron collisions [3, 4, 5, 6, 7]. This calls for a factorised description of high- P_T J/ψ beyond leading power [8]. The effect of QCD corrections is also manifest in the polarisation predictions. While the J/ψ and Υ produced inclusively or in association with a photon are predicted to be transversely polarised at LO, it has been found that their polarisation at NLO is increasingly longitudinal when P_T gets larger [5, 6, 9]. In recent works [10, 11], we have also shown that the CSM alone is sufficient to account for the magnitude of $d\sigma/dy$ at RHIC, Tevatron and LHC energies.

We evaluate here the P_T dependence of the J/ψ yield and its polarisation at Tevatron and LHC energies. We describe the procedure used to obtain a first evaluation of some dominant contributions at α_s^5 (NNLO^{*}) in addition to the yield at NLO (up to α_s^4). We then compare available data from the Tevatron and the LHC with our results: the direct yields differential in P_T along with the polarisation vs P_T for the prompt yield using an essentially data-driven estimation of the polarisation for J/ψ from χ_c .

2. Cross-section

For the NLO cross section, we use the partonic matrix elements of [3]. In order to investigate the expected impact of NNLO QCD corrections for increasing P_T , we also present the NLO results plus the real-emission contributions at α_s^5 evaluated along the lines of [6], referred to as NNLO^{*}. At α_s^5 , the last[‡] kinematically-enhanced topologies open up, with a P_T^{-4} fall off of $d\sigma/dP_T^2$. The procedure used here for the NNLO^{*} is exactly that of [6]: the real-emission contributions at α_s^5 are evaluated using MADONIA [12] by imposing a lower bound on the invariant-mass squared of any light partons (s_{ij}). The dependence on this cut should decrease for larger P_T since no collinear or soft divergences can appear there for the new channels opening up at α_s^5 with a leading- P_T behaviour, *i.e.* the ones which interest us. For other channels, whose Born contribution is at α_s^3 or α_s^4 , the cut would produce logarithms of s_{ij}/s_{ij}^{\min} . These are not necessarily small, but they are expected to be factorised over their corresponding Born contribution, which scales as P_T^{-8} or P_T^{-6} . They are thus suppressed by at least two powers of P_T with respect of the leading- P_T contributions (P_T^{-4}). The sensitivity on s_{ij}^{\min} is expected to be small at large P_T .

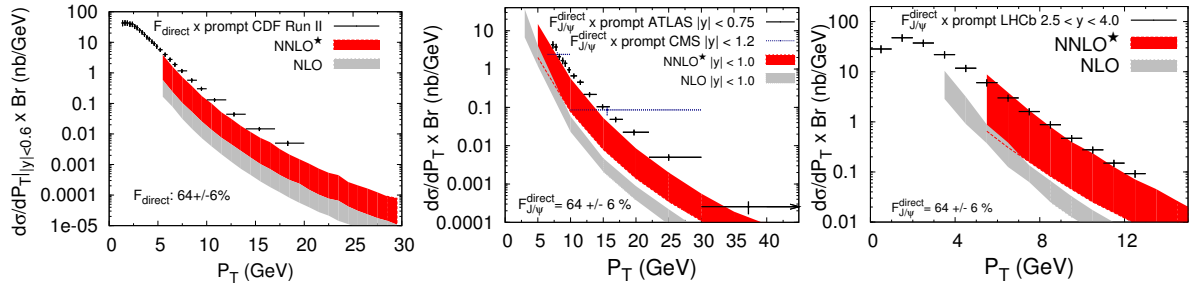


Figure 1: $d\sigma/dP_T \times \text{Br}$ for direct J/ψ production from NLO and NNLO^{*} CS contributions at $\sqrt{s} = 1.96$ TeV (left) and at $\sqrt{s} = 7$ TeV for central (middle) and forward (right) rapidities. These are compared to the CDF [14], ATLAS, CMS and LHCb data [15, 16, 17] multiplied by a constant direct fraction from CDF [18]. See text for details on theoretical-error bands.

Our results are shown on Fig. 1. The CSM is very close to the existing data, if the upper range of the NNLO^{*} is a relevant evaluation of the NNLO. The uncertainty bands at NLO are obtained from the *combined* variations of the charm-quark mass ($m_c = 1.5 \pm 0.1$ GeV), the factorisation μ_F and the renormalisation μ_R scales chosen in the couples $((0.75, 0.75); (1, 1); (1, 2); (2, 1); (2, 2)) \times m_T$ with $m_T^2 = 4m_Q^2 + P_T^2$. The band for the NNLO^{*} is obtained using a combined variation of m_c , $0.5m_T < \mu_R = \mu_F < 2m_T$ and $2.25 < s_{ij}^{\min} < 9.00$ GeV². We have used the NLO set CTEQ6.M [13] and have taken $|R_{J/\psi}(0)|^2 = 1.01$ GeV³ and $\text{Br}(J/\psi \rightarrow \ell^+ \ell^-) = 0.0594$.

[‡] We do not expect any further kinematical enhancement as regards the P_T dependence when going further in the α_s expansion: P_T^{-4} is the slowest possible fall-off. Above α_s^5 , usual expectations for the impact of QCD corrections would then hold. One would expect a K factor multiplying the yield at NNLO accuracy, which would be independent of P_T and of a similar size as those of other QCD processes. A further enhancement by an order of magnitude between the NNLO and N³LO results would be quite worrisome.

3. Polarisation

The polarisation parameter α is extracted bin by bin in y or P_T from the normalised distribution of the polar angle θ between the ℓ^+ direction in the J/ψ rest frame and its direction in the laboratory frame, $I(\cos \theta) = \frac{3}{2(\alpha+3)}(1 + \alpha \cos^2 \theta)$. We thus work in the helicity frame. α is also related to a ratio of the polarised cross sections: $\alpha = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}$.

For the time being, there does not exist any measurement of direct J/ψ polarisation, *i.e.* after the extraction of the χ_c feed-downs (up to 30-40 %) which may strongly impact on the observed values of α . It is however possible to constrain its effects by using existing data on $\sigma_{\chi_{c1}}/\sigma_{\chi_{c2}}$ and by relying on E1 dominance for the transition $\chi_c \rightarrow J/\psi + \gamma$.

Indeed, using E1 dominance [19], one can obtain [21] a range of the yield of longitudinally (transversely) polarised J/ψ in terms of simple relations involving the polarised χ_c yields. Allowing for extreme cases, these relations allow the yield from χ_c to be fully transversely polarised, while there is a minimal value of α . Following the discussion of [21] and taking $R_{12} = \frac{\sigma_{\chi_{c1}} \text{Br}(\chi_{c1} \rightarrow J/\psi \gamma)}{\sigma_{\chi_{c2}} \text{Br}(\chi_{c2} \rightarrow J/\psi \gamma)} = 2.5 \pm 0.1$ [20], one obtains $\alpha_{\text{from } \chi_c}^{\text{min}} \simeq -0.42$, rather different than -1.

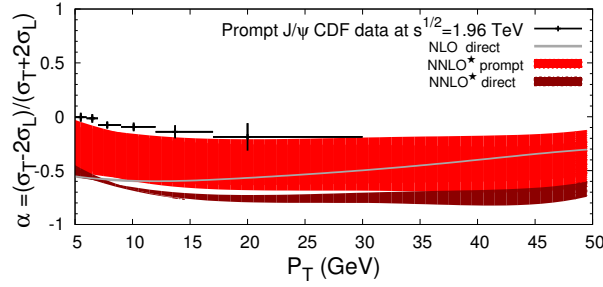


Figure 2: Comparison between the extrapolation of α for prompt J/ψ in pp at $\sqrt{s} = 1.96$ TeV (red band), the direct NLO α (gray line), the direct NNLO* α (thinner dark-red band) and the CDF data [22] for prompt J/ψ .

Since 30% of the J/ψ come from χ_c nearly independent of P_T in the range considered here [18], we expect a partial contribution to the polarisation ranging from $0.3 \times (+1)$ to $0.3 \times (-0.42)$. Regarding the other 70%, one multiplies the result for the direct yields by 0.7, since the polarisation of J/ψ from $\psi(2S)$ is expected to be identical to the direct one. Doing so, one obtains the extrapolation shown on Fig. 2. If the J/ψ from χ_c yield is strongly transversely polarised (the upper limit), the polarisation of the prompt yield is in rather good agreement with the data.

4. Conclusion

We have evaluated the NLO and NNLO* J/ψ yield at Tevatron and LHC energies. As found for Υ at the Tevatron [6] and for J/ψ at RHIC [21], the upper bound of the CSM predictions is very close to the experimental data from CDF, ATLAS, CMS and LHCb. However, the

NNLO^{*} evaluation is not a complete NNLO calculation. It is affected by logs of an IR cut-off whose effect might not vanish as quickly as one has anticipated. It may very well be that the upper limit of the prediction –close to the data– accurately reproduces the complete NNLO yield, or that the lower limit –close to the NLO yield– reproduces the NNLO yield. If the upper limit of the NNLO^{*} does indeed overestimate the NNLO, the CSM alone is likely insufficient to account for the data. Conversely, the CSM alone is enough and the colour-octet contributions are not required.

As regards polarisation, we have derived a range for the prompt yield polarisation. This range is affected by admittedly large theoretical uncertainties, but the upper edge – corresponding to a transversely polarised feed-down– is in rather good agreement with the data from the Tevatron. We recall that the trend for a longitudinally (direct) $\psi(2S)$ yield [22] was also met by the NNLO^{*} [7].

In conclusion, the CSM may very well provide a good description of J/ψ production in high-energy pp collisions, both in terms of the cross section and the yield polarisation.

Acknowledgments We thank P. Artoisenet, J. Campbell, F. Maltoni and F. Tramontano for our fruitful collaboration on [6], from which the study presented here is derived. We acknowledge the support of the ReteQuarkonii Networking of the EU I3 HP 2 program.

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